The Transition Between X-ray Emission Regimes in the M34 Open Cluster

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Abstract. I report on a correlation between the saturated and non-saturated regimes of X-ray emission and the rotation sequences that have been observed in the M34 open cluster from extensive rotation periods surveys. An interpretation of this correlation in term of a transition between different dynamo regimes in the early stage of evolution on the main sequence is proposed.

1. Introduction

The present paper summarises the results of a study of the X-ray coronal emission in the M34 open cluster. M34 (NGC 1039) is located at a distance of about 470 pc (Jones et al. 1996). Its metallicity is close to solar (Schuler et al. 2003). Its age between 177 Myr (Meynet et al. 1993) and 251 Myr (Ianna & Schlemmer 1993) is intermediate between that of the Pleiades ($\sim$ 125 Myrs) and that of the Hyades ($\sim$ 625 Myrs).

While stars in the Pleiades rotateat rates between 0.2 and 10 days (Hartman et al. 2010), stars in the Hyades are in general much slower rotators (Delorme et al. 2011). During the $\sim$ 500 Myrs time interval that separates these two clusters, late-type stars such as those present in M34 thus undergo significant changes in their surface rotation rate. These changes are the visible signature of modifications of their internal rotation profiles. These, in turn, could affect the dynamo processes that operate in their interiors, possibly altering the level of magnetic activity in their outer atmospheres. The purpose of the study was to look for the X-ray signatures of such possible modifications.

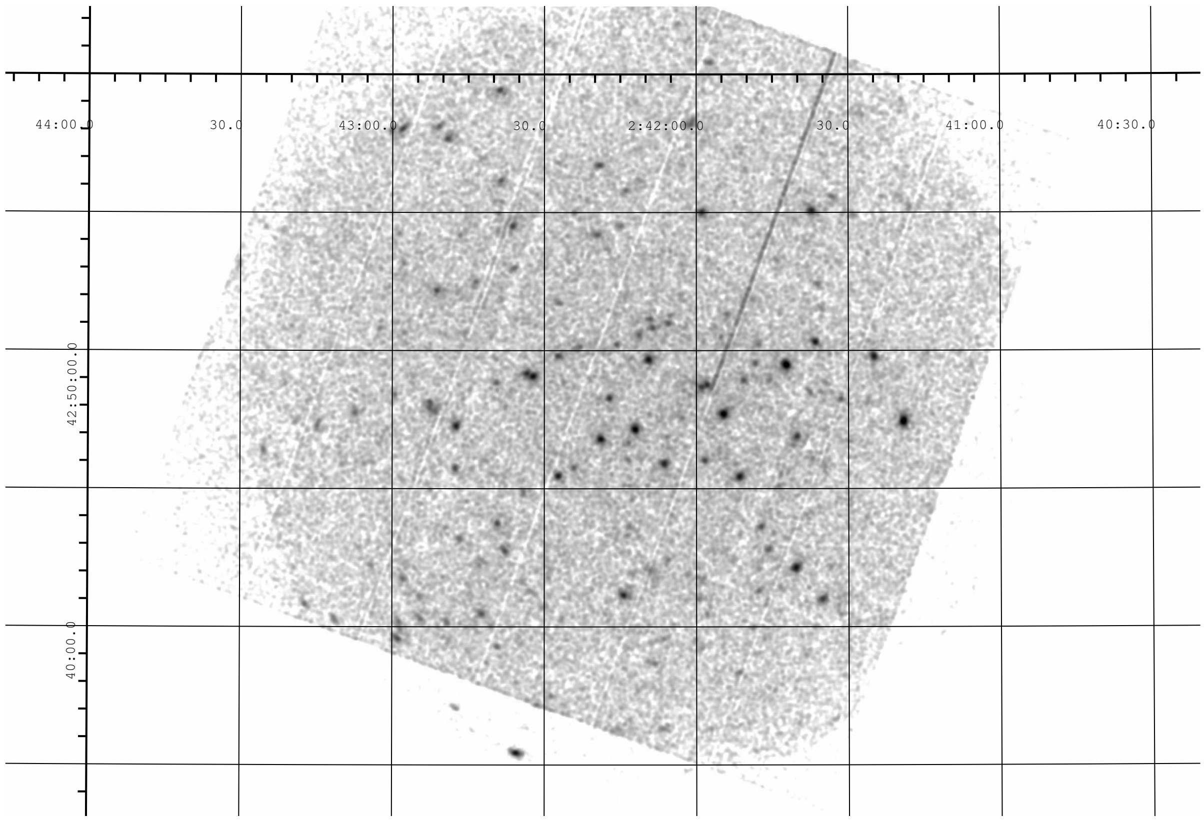

Figure .1: Combined MOS1, MOS2, and PN image of NGC 1039 in the 0.5 to 4.5 keV band.

2. Observations

M34 was observed with the EPIC pn and the two EPIC MOS cameras on board the $XMM-Newton$ space observatory (Jansen et al. 2001) The EPIC pn and MOS exposure times were 42 ksec and 39 ksec, respectively (see Figure .1). A "thick" aluminum filter was used in front of the cameras to reject visible light from the stars. Detection was made of 189 X-ray sources that are listed in the $XMM-Newton$ Serendipitous Source Catalog (Watson et al. 2009).

The X-ray data were complemented with recent measurement results of stellar rotation periods. The $XMM-Newton$ X-ray source list was first correlated with the list of 83 kinematic and photometric late-type M34 cluster members with known rotation periods established by Meibom et al. (2011). It was then correlated with the results of a time series photometric survey of M34 in the V- and i- bands reported by Irwin et al. (2006). Finally, the list was correlated with the list of 55 solar-type stars in M34, whose rotation periods were derived from differential photometry by James et al. (2010). In total, 41 stellar members of the M34 open cluster have been found that have known rotational periods and for which X-ray emission has been detected.

X-ray fluxes were derived from the source count rates using energy conversion factors (ECF). These ECFs were calculated using the Portable, Interactive, Multi-Mission Simulator (Mukai 1993) in the 0.5-4.5 keV range for optically thin plasmas with temperatures

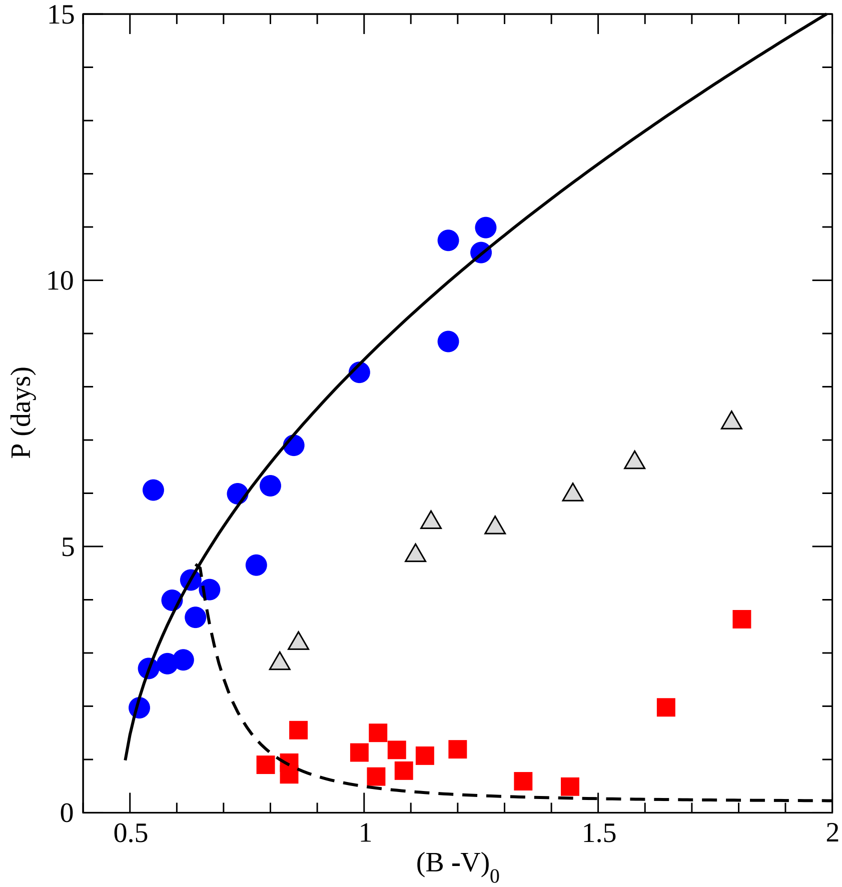

Figure .2: Rotation periods vs. (B−V) indices of the M34 sample stars. The solid line represents the I sequence defined by Barnes (2007). The dashed line represents the C sequence determined by Meibom et al.(2011). M34 stars represented as blue circles and red squares were classified as I and C sequence stars, respectively. Grey triangles represent gap stars assumed to be evolving from the C to the I sequence.

comparable to those found in the spectral fitting of active stellar coronae (Gondoin 2006). The absorbing hydrogen column density towards M34 was estimated from the reddening correction E_{B-V} = 0.07 (Canterna et al. 1979) to about 3.4 × 10^{20} cm^{-2}. For absorbing hydrogen column densities lower than 10^{21} cm^{-2}, the energy conversion factor of the EPIC pn camera equipped with a thick filter in the 0.5-4.5 keV band is flat and well approximated by ECF = 3.7 × 10^{11} counts erg^{-1} cm^2 for plasma temperatures in the range (4-25) × 10^6 K (Gondoin 2006). The X-ray fluxes were then converted into stellar X-ray luminosities assuming a distance of 470 pc (Jones et al. 1996).

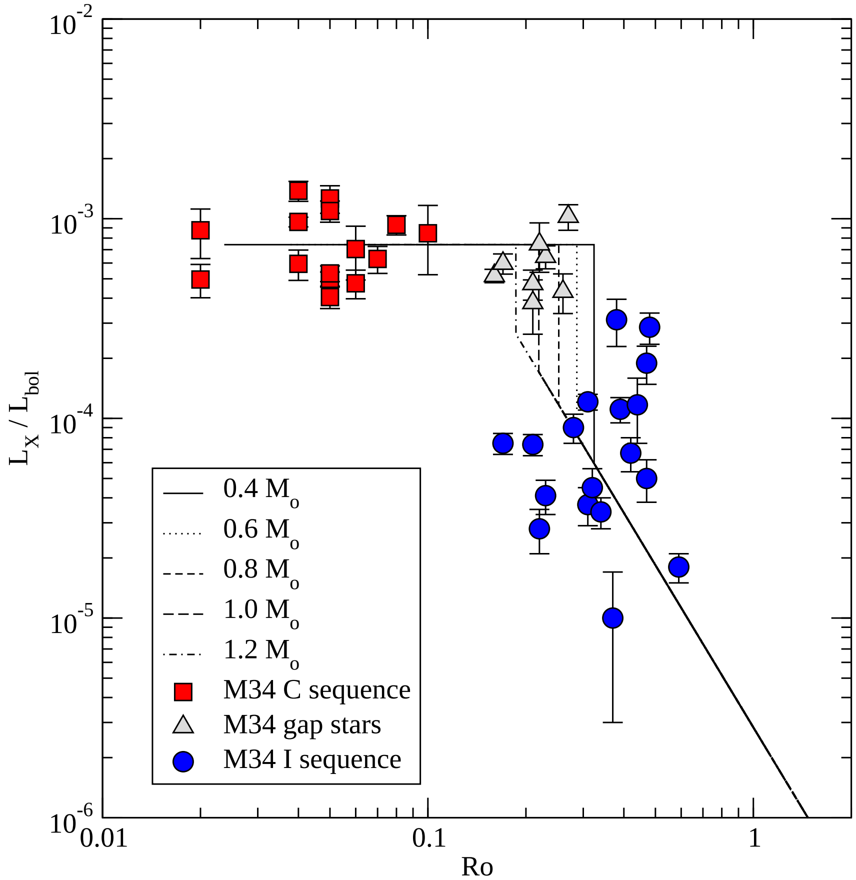

Figure .3: X-ray to bolometric luminosity ratio vs Rossby number of the sample stars compared with a model of X-ray activity evolution (Gondoin 2013) for stars with masses between 0.4 and 1.2 $M_\odot$ having an initial period of rotation of 1.1 days on the ZAMS.

3. Analysis

The X-ray luminosities of F5 through M5 main-sequence stars relative to their bolometric luminosities have been found to depend on their Rossby numbers (Patten & Simon 1996); (Randich 2000). This number ($Ro = P_{\rm rot}/\ \tau_{\rm c}$) is an important indicator in hydromagnetic dynamo theory that measures the extent to which rotation can induce both helicity and differential rotation, which are considered essential for a solar-type dynamo. While the stellar rotation period $P_{\rm rot}$ can be directly measured, $\tau_{\rm c}$ is sometimes derived from the mixing-length theory (Kim & Demarque 1996) and usually empirically determined. A relationship between stellar mass and convective turnover time was recently derived by Wright et al. (2011) that is valid over the range $0.09\ M_\odot < M < 1.36\ M_\odot$. It is scaled such that values of $\tau_{\rm c}$ for solar-mass stars match those of Noyes et al. (1984) for the Sun. This relationship was used to estimate the Rossby numbers of the sample stars.

Young stars tend to group into two main sub-populations that lie on narrow sequences in diagrams where the measured rotation periods of the members of a stellar cluster are plotted against their B − V colors (Barnes 2003); (Meibom et al. 2009). One sequence, called the I sequence, consists of stars that form a diagonal band of increasing period with increasing B − V color. In young clusters, another sequence of ultra-fast rotators called the C sequence, is also observed, bifurcating away from the I sequence towards shorter rotation periods. Some stars lie in the intervening gap between the I and C sequences.

Figure .2 shows the rotational periods P_{rot} of the sample stars as a function of their reddening corrected $(\mathrm{B}-\mathrm{V})_0$ indices. It also displays the rotational isochrones of the I and C sequences. Their functional forms were first introduced by Barnes (2003a). For the I sequence, I used the form subsequently modified by Barnes (2007) in line with the gyrochronology analysis of M34 performed by (Meibom et al. 2011). The proximity of the M34 data points to these curves was used to determine their membership to the C and I sequences or the gap between them.

Figure .3 displays the X-ray to bolometric luminosity ratio vs Rossby number diagram of the M34 sample stars, distinguishing members of the I sequence, of the C sequence and of the gap. It shows a correlation between the X-ray emission regimes and rotation sequence classification. Indeed, members of the C sequence have small Rossby numbers ($Ro < 0.1$) and X-ray to bolometric luminosity ratios close to the 10^{-3} saturation level. Members of the I sequence, in contrast, have larger Rossby numbers ($Ro \geq 0.17$) and X-ray to bolometric luminosity ratios significantly smaller than the saturation limit.

Gap stars occupy an intermediary position in the $L_{\mathrm{X}}/L_{\mathrm{bol}}$ vs. Ro diagrams. On the one hand, gap stars have Rossby number ($Ro \geq 0.17$) in the same range as those of some I sequence stars. They would therefore be expected to operate in a non-saturated regime of X-ray emission. On the other hand, their X-ray to bolometric luminosity ratio is similar to those of C sequence stars, i.e., close to the saturation level.

4. Discussion

A correlation between rotation sequences (see Figure .2) and X-ray emission regimes (see Figure .3) is observed among main sequence stars in the M34 open cluster. A steep transition in the $L_{\mathrm{X}}/L_{\mathrm{bol}}$ ratio is detected between the C sequence and gap stars that emit close to the 10^{-3} saturation level, and the I sequence stars, whose $L_{\mathrm{X}}/L_{\mathrm{bol}}$ ratio is significantly lower. The $L_{\mathrm{X}}/L_{\mathrm{bol}}$ ratio is a lower limit of the ratio between the surface magnetic flux and the outer convective flux (Gondoin 2012). A decrease of this ratio around $Ro \approx 0.14$ - 0.4 is thus indicative of a drop in dynamo efficiency.

Independently from any specific model of stellar rotation evolution, the clustering of main-sequence stars in M34 into fast and slow rotation sequences in period vs colour index diagrams, and the low density of stars in the gap indicate that stars spend less time in this part of the diagram than on the C and I sequences. The transition from the C to the I sequence thus constitutes an evidence for a brief phase of strong surface rotation deceleration among some of the late-G and K type stars in M34. Such a decay is most likely due to rotational braking by stellar wind. If the magnetic field lines that sling charged particles from the wind into space are rooted in the photosphere, the convective envelope rotation should be decelerated by the wind torque more efficiently than the radiative core which is kept in rapid rotation by the conservation of angular momentum . Young stars shall thus develop a strong gradient in angular velocity at the base of the convection zone. Such a gradient is an essential ingredient for the generation of an interface dynamo at the base of the convection zone (Spruit 2002).

According to a scenario described in Gondoin (2013), the correlation between rotation sequences and X-ray emission regimes would thus result from the co-existence of two dynamo processes among M34 stars, i.e. a boundary-layer interface dynamo and a convective envelope turbulent dynamo. This last process dominates in rapidly rotating C sequence stars. As the shear between the fast spinning radiative interior and the convective envelope increases during the transition of gap stars from the C to the I sequence, another process strengthens in which dynamo action occurs in the boundary region between the radiative core and the convective envelope. This dynamo process relies on differential rotation, but also induces important redistributions of angular momentum. As the stars reach the I sequence and the rotation of their convective envelope decays, the turbulent dynamo is quenched and the interface dynamo becomes dominant, decreasing progressively at later stages of evolution when rotation dies away.

Acknowledgements. I am grateful to the Organising Committees of the "Cool Stars 18" workshop for allowing me to present this work.

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